Green River FLO-2D Discharge Routing Model
Flaming Gorge Dam to Colorado River Confluence

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Executive Summary

A two-dimensional flow hydrograph routing model was developed for the Green River system from Flaming Gorge to the Colorado River confluence, a distance of 412 miles. The model called FLO-2D was designed and developed by FLO Engineering, Inc. FLO-2D is a two-dimensional, finite difference flood routing model which simulates a discharge hydrograph with very small timesteps on the order of 30 seconds to one minute. The model uses a digital map base to establish a flow domain system of uniform grid elements. Channel flow is simulated using a channel geometry relationships reflective of the natural channel shape. Overbank and return flow discharges are computed to assess floodplain inundation and floodwave attenuation. The model also simulates infiltration losses and conserves volume.

There were three essential data components required to develop the FLO-2D simulation model for the Green River. These data bases included developing a digital topographic map of the river and floodplain, compiling all the cross section surveys and preparing the tributary and mainstem flow hydrograph data files. The Green River map resources were reviewed and the USGS 7.5 minute series of 40 maps was selected to create the base map. These maps proved to have the best topographic resolution of the entire river system. The base map was digitized in AutoCAD version 12. All the available cross section survey data was compiled from various river researchers. This data was organized by river reach and analyzed for channel geometry relationships as a function of flow depth. The data base was then used to assigned channel geometry to the FLO-2D channel grid elements which were not associated with a surveyed cross section. Finally, all the available USGS tributary inflow data was compiled as input to the model. This daily hydrograph data was supplemented with Flaming Gorge Dam releases and level logger discharge monitoring data at several locations in the Green River system.

The FLO-2D grid system consisted of 2,482 - 2,000 ft square grid elements including 962 channel elements to simulate a discharge hydrograph every 2,000 ft of channel in the Green River system. The initial FLO-2D calibration run encompassed 100 days of the 1996 high flow season. Following calibration of the roughness values and infiltration parameters and some adjustment of floodplain elevations and channel geometry for 1996, the FLO-2D model and data base was used to simulate 100 days of the 1997 Green River hydrograph. The flood simulations included the prediction of overbank flood inundation. Based on the excellent correlation between the 1997 measured data and the FLO-2D predicted discharge hydrograph at the USGS Jensen and Green River gages, the Green River FLO-2D model was applied to the 1997 unregulated discharge Green River discharge at Greendale, Wyoming. FLO-2D hydrographs were predicted for flows without the storage effects of Flaming Gorge and Fontenelle Reservoirs in Wyoming and for the flow scenario where the Green River discharge was limited to the maximum Flaming Gorge jet tube release.

The Green River routing model is now available to simulate any historical or predictive flow scenario. This tool can be used to evaluate the effects of Flaming Gorge releases on magnitude, timing, and duration of various discharges to benefit fish habitat and enhance floodplain inundation. The model can applied to evaluate Recovery Program flow recommendations for the Green River system and its tributaries.

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List of Key Words

FLO-2D, Green River, flood routing, hydrograph simulation, two-dimensional flow routing, dynamic wave, floodwave attenuation, floodplain inundation, numerical modeling, discharge prediction, peak discharge, high flows

Project Funding and Support

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Introduction

The National Park Service and the US Fish and Wildlife Service supported the development of a discharge routing model for the Green River in Utah from Flaming Gorge Dam to the confluence of the Colorado River. A two-dimensional finite difference flow routing model FLO-2D was developed for the Green River for the 1996 and 1997 water years. FLO-2D is a multifaceted channel and overland flow routing model created by FLO Engineering. The model has channel-floodplain interface to compute overbank discharge. Unconfined overland flow is routed over complex topography and roughness in eight directions. Channel flow is routed through natural cross sections computing flow depths and velocities for relatively small timesteps. FLO-2D routes the Flaming Gorge Dam release hydrograph and all the tributary hydrographs with a full dynamic wave approximation to the momentum equation, conserving volume and predicting areas of overbank inundation.

To develop the routing model application for the Green River a digitized map of the river and floodplain topography had to be prepared. After an extensive search of mapping resources, it was determined that the USGS 7.5 minute quad maps were best available maps that covered the entire river basin. The contour interval for the maps varied from 10 ft to 40 ft. After the base map was digitized in a computer-aided design and drafting software program (CADD), a survey grid system of uniform elements was overlaid on the digitized contours. To prepare the channel data base for the model, all available Green River channel cross section surveys were compiled and analyzed for channel geometry relationships. Cross section channel geometry were then assigned to each channel grid element.

Discharge inflow for the FLO-2D Green River model is the USGS mean daily hydrograph data. River flow data includes Flaming Gorge Dam releases and discharge records at Jensen and Green River. Tributary inflow includes the Yampa, Duchesne, White, Price and San Rafael Rivers and Brush and Ashley Creeks. All other small tributary inflow was omitted because of the lack of discharge records. To further monitor the flows in the Green River and calibrate the FLO-2D model, a series of level logger stage recorders were installed throughout the middle and lower Green Rivers in both 1996 and 1997. These level loggers were erected in Echo Park, Ouray National Wildlife Refuge, below the White River, in Desolation Canyon at McPherson Ranch and in Canyonlands National Monument near Bonita Bend. Combined with the USGS Jensen and Green River gages, the level loggers provide estimates of the high flow discharge hydrograph throughout the Green River with the longest ungaged reach being less than 90 miles.

This report discusses project goals and objectives, describes the study area, and presents a description of the FLO-2D model, data file creation, model calibration and results. The FLO-2D model, Green River data files, CADD mapping and flow simulation results can be obtained by contacting FLO Engineering, Inc. A FLO-2D Users Manual accompanies this report.

Project Goals and Objectives

The project goal was to develop a modeling tool to predict the seasonal flow hydrograph at any location in the Green River downstream of Flaming Gorge Dam on a daily basis. Once the FLO-2D data base was developed, several project objectives could be accomplished including:

- Calibration of the model for the 1996 high flow season.
- A review of the model accuracy by simulating the 1997 high flow data.
- An estimate of floodplain inundation area for these two flow years.
- Simulation of the Flaming Gorge jet tube releases.
- Prediction of discharge, timing and duration at any location in the Green River.

The Channel Monitoring Program data base compiled over the past several years was used to calibrate and improve the accuracy of the flow routing simulation. This included the channel cross section data and level logger discharge data collected at various locations in the Green River. The cross section data was used to establish the channel geometry parameters for every channel grid element in the model. The level logger data was applied to improve the calibration of the FLO-2D model in the various subreaches of the system.

Green River Study Area

The Green River project study area extends from Flaming Gorge Dam in Wyoming to the Colorado River confluence in Utah. FLO-2D will route the flow in the mainstem channel and the overland flow on the floodplain. Within the Green River canyons and valleys, all the floodplain that could be potentially inundated by a flood of record was considered for the potential flow domain. None of the Green River tributaries were modeled in the FLO-2D simulation. The tributary inflow hydrographs were input as inflow to specific mainstem channel grid elements. The Green River has several distinctive reaches based on geology, canyon morphology and river bed slope which can identified as follows:

- Red Canyon reach from Flaming Gorge to Lodore Canyon
- Lodore Canyon
- Whirlpool Canyon including Echo Park and Whirlpool Canyon
- Island Park and Rainbow Park reach
- Split Mountain reach
- Flooded bottomlands reach from Split Mountain to the Sand Wash
- Desolation Canyon reach from Sand Wash to Green River
- Canyonlands reach from Green River to the Colorado River confluence.

The unique channel morphology in these reaches were considered when assigning channel geometry and hydraulic roughness values.

Overview of the FLO-2D Flood Routing Model

FLO-2D is a physical process, finite difference numerical model which routes rainfall-runoff and flood hydrographs over unconfined surfaces or in conveyance channels. It simulates the progression of a flood hydrograph, conserving flow volume over a system of square grid elements. One-dimensional channel flow is routed in either rectangular, trapezoidal or natural-shaped channels using a diffusive or dynamic wave approximation to the momentum equation. Overland flow is routed in eight directions either as sheet flow or as flow in multiple channels (rills and gullies) using either the kinematic or the diffusive wave approximation to the momentum equation. Channel overbank flow is computed when the channel capacity is exceeded. Predicted flow depth and velocity between grid elements represent average hydraulic values computed for a small timestep (on the order of minutes or seconds). The timesteps are incremented and decremented during a flood simulation to maintain numerical stability.

FLO-2D can applied for projects involving river channel overbank flooding, alluvial fan flows, flow through urban areas or for the hydraulic design of flood mitigation measures. The model has number of components which will add detail to a flood simulation including channel-floodplain discharge exchange, loss of storage due to buildings or topography, flow obstruction, rill and gully flow, street flow, bridge and culvert flow, levee and levee failure, mud and debris flow, sediment transport, rainfall and infiltration. The important FLO-2D components utilized in this project include channel-floodplain flow exchange, infiltration and loss of storage related to topography. Very detailed flow hydraulics such as hydraulic jumps, flow in river bends or around bridge piers can not be simulated with the model. FLO-2D does not distinguish between subcritical or supercritical flow and has no restrictions when computing the transition between the flow regimes. Flow over adverse slopes, ponding and backwater effects can be simulated.

With the output files of a FLO-2D flood simulation, maximum flow depths and velocities can be mapped directly on the digitized base map. It provides engineers and hydrologists with a tool to predict the area of floodplain inundation for various return period frequency flood events. Flow hydrographs can be predicted at any location or grid element in the system. A detailed users manual has been prepared which describes the model, its application and the creation of the input data files. For further information regarding the model consult the manual or contact FLO Engineering, Inc. The development of the FLO-2D data files and the output results for this Green River project are described in the following sections.

FLO-2D Data File Development

FLO-2D requires three essential and substantial data bases including hydrology as either rainfall or runoff, floodplain topography and channel geometry. For simulating Green River daily flow hydrographs, the tributary inflow and the Flaming Gorge Dam releases were input as a mean daily discharge. This task required obtaining USGS gaging station data to prepare as the FLO-2D inflow data files. For 1996, the tributary inflow included the Yampa River (represented by the combined flows of the Yampa River at Maybell and the Little Snake River at Lily), Duchesne River, White River, Price River and San Rafael River. In addition, two smaller tributaries, Brush Creek and Ashley Creek, had 1996 discharge records which were also prepared as data files. Smaller creeks such as Jones Hole and Vermillion Creek did not have discharge records. The Yampa River flow at Maybell was lagged by two days and the Little Snake at Lily was lagged by one day and the combined flow was input to the simulation model at the Green and Yampa River confluence. The rest of the tributary inflow was input at the Green River confluence without a time lag. No rainfall or storm inflow was simulated.

A FLO-2D simulation requires a grid system of uniform grid elements whose individual surface is represented by an elevation and an overland roughness value. To prepare the grid system flow domain, an appropriate topographic map base must be digitized. After several months of review of potential map resources, it was decided that the USGS quad maps with (20 ft and 40 ft contours) were the most detailed maps available that covered the entire study reach of the Green River and its floodplains. This search included the recently completed digital maps for the state of Utah which were determined to be of poor quality with respect to the river system. Unfortunately, the USGS map contour resolution was very course for the relatively flat floodplain. This lack of topographic detail effects of the prediction of floodplain inundation. In the future, as more detail mapping becomes available, the base map can be improved and grid element elevations can be adjusted.

Forty 7.5 minute USGS topographical maps were purchased. These maps were digitized at the FLO Engineering Breckenridge Office using AutoCAD-DCA (version 12). The digitized base maps include the river outline, floodplain contours, tributary confluence and important features such as bridges, USGS gaging stations, unique sites names (i.e. Lodore Canyon). A centerline of the river was created and then delineated into one mile segments with the Colorado River confluence assigned a starting position of 0.0 miles which resulted in Flaming Gorge Dam being located at river mile 412.2.

The maps were carefully reviewed and revised where necessary and then a triangular irregular network (TIN) was prepared with the CADD program. A two thousand foot square grid system was overlaid on the digitized based map resulting in 2,482 grid elements. Although a more detailed grid system of 500 ft or 1,000 ft grid elements could have been used, a 2,000 ft grid element system was selected because the USGS contour intervals would not support a higher resolution grid system. The grid elements were assigned grid element numbers and elevations which were then reviewed for accuracy. A number of the grid element floodplain elevations were adjusted because the assigned grid elevation did not accurately reflect the floodplain surface. The next step was to assign the river channel to the appropriate grid elements and create a channel geometry data base. Every channel element (total of 962 channel elements) had to be assigned representative channel geometry, channel length within the grid element, and channel roughness. Refer to the FLO-2D manual for a complete description of all the channel data associated with a channel element.

To assign channel geometry to each channel grid element, it is was necessary to compile all the available channel cross section data. Green River cross section surveys have been concentrated in several locations including: the flooded bottomlands reach extending from about Split Mountain to Ouray Bridge, the lower portion of the Green River in Canyonlands National Monument, Lodore Canyon, Echo Park, Whirlpool Canyon, Island and Rainbow Parks and a few reaches in Desolation

Canyon. The river reaches with limited cross section data include the Flaming Gorge to Lodore Canyon reach, portions of Desolation Canyon, the reach in the vicinity of Green River and the reach between San Rafael to Mineral Bottom in Canyonlands. All the cross section survey data was reduced to a common data base and the cross section channel geometry regression relationships were computed using the XSEC pre-processor program available with the FLO-2D modeling system. The channel geometry power relationships include:

$$A = a\, d^b \qquad A = a\, P^b \qquad P = a\, d^b \qquad T = a\, d^b$$

where A is the cross section flow area, P is the wetted perimeter, T is the top width, d is the channel depth, a is the regression coefficient and b is the regression exponent. The regression relationships are computed in the XSEC processor program by using a series of 40 horizontal slices starting at the channel bottom and applying a least squares-fit algorithm to generate the power functions. Almost all of the correlation coefficients for these relationships are 0.95 or greater. These regression relationships are applied in the FLO-2D model in place of interpolating the actual cross section data to determine the flow hydraulics. This method saves computation time without any loss of accuracy. All the cross section channel geometry is presented in Appendices A and B.

Each channel grid element must be assigned a set of cross section regression relationships. The 268 surveyed cross sections covered only a portion of the entire Green River consisting of 962 channel grid elements. The surveyed cross sections were located on the digitized base map and assigned to the nearest channel grid element. To assign channel geometry to those grid elements where no cross sections had been surveyed, the Green River was divided into three discharge reaches: Flaming Gorge to the Yampa River confluence, Yampa River to the White River confluence and the White River to the Colorado River confluence. The cross section data for each reach was divided into 100 ft width categories (e.g. width < 300 ft; 300 ft < width < 400 ft; ... ; 800 ft < width). The channel geometry regression coefficients and exponents for each reach was averaged. Based on the river width as measured on the base map, the average channel geometry regression relationships were then assigned to every channel grid element without a surveyed cross section.

To complete the FLO-2D data file development, the control, infiltration and storage area reduction data files were created. The control data includes simulation time, output interval time, control switches for infiltration, number of channel elements and numerical stability data. The infiltration data includes hydraulic conductivity, soil suction, porosity, and other related data. Finally, the area and width reduction factors enables refinement of the potential flood storage area and definition of flow path obstruction for the floodplain grid elements.

FLO-2D Model Assumptions and Limitations

To apply the FLO-2D model to the Green River system several assumptions regarding the data base and model capabilities had to incorporated into simulation. The primary assumption pertains to the selection of the grid element size. Each 2000 ft square gird element of floodplain is represented by single elevation and hydraulic roughness. Small variations in the topography within the grid element are neglected. With respect to the channel, the assigned cross section channel geometry represents the entire channel length within the element and variations of the cross section within the channel grid element are ignored.

Although FLO-2D has the capability to simulate watershed rainfall/runoff hydrology, no storm activity within the Green River basin was modeled. It is recognized that the USGS gaging station discharge data at Jensen and Green River or the various level loggers could reflect some intervening storm runoff flows from a summer convective thunderstorm. Storm runoff spikes may appear in the known hydrograph data.

Several other assumptions involve physical processes of the river. This initial application of the FLO-2D model to the Green River assumes a rigid bed boundary and thus sediment transport is not simulated. FLO-2D has a sediment transport component and future model applications are anticipated to model sediment movement in the Green River system. Evaporation is not simulated by the FLO-2D model but flow volume losses attributed to evaporation, bank storage and channel infiltration can be estimated by appropriate calibration of the infiltration parameters.

Green River FLO-2D Model Calibration

Green River flows were simulated for 100 days of the 1996 high flow season starting on April 1 and ending on July 9. To monitor the accuracy of the flow simulation, a post-processor program called HYDROG is used. HYDROG plots the computer hydrographs for every channel grid element. By preparing a data file for the HYDROG program, the predicted hydrographs can be compared with measured discharge hydrographs. In 1996, five level loggers for monitoring river stage were established throughout the Green River system (at Echo Park, at the Ouray National Wildlife Refuge, just downstream of the White River confluence, in Desolation Canyon at McPherson Ranch and at Bonita Bend in Canyonlands National Park). A limited number of discharge measurements were collected at each level logger to create a discharge rating curve (see FLO Engineering, 1997). When these five level loggers are combined with the USGS gages at Jensen and Green River, they constitute a system of seven known discharge points with which to calibrate the FLO-2D predicted hydrograph. The HYDROG program provides a convenient graphical display for the Green River predicted daily discharge for every 2000 ft along the river channel.

After reviewing the HYDROG plotted hydrographs, channel roughness and infiltration parameters were adjusted within acceptable ranges to calibrate the predicted hydrograph at the seven points of known discharge in the Green River. Generally, the final Manning's n-value ranged from 0.024 to 0.050 with the higher n-values assigned to grid elements in the steep canyon reaches. The infiltration hydraulic conductivity was assigned a value of 0.04 in/hr uniformly throughout the river system for both the floodplain and channel grid elements. Although FLO-2D can have accommodate spatial variability using the Green-Ampt infiltration model, the infiltration parameters were uniformly assigned. Infiltration estimates can further refined in future Green River simulations. The hydraulic conductivity was varied slightly to increase or decrease the estimated losses to improve the correlation between the predicted and known hydrographs.

Some channel element cross sections and roughness values were adjusted to reduced the abrupt transition between grid elements. Since some of the channel elements were assigned average cross section geometry for the reach, then in some cases, the channel slope, and Manning’s roughness n-values were mismatched. This mismatching and abrupt cross section transitions can cause numerical surging in the model. Numerical surging is the brief slugging of flow between two grid channel grid elements when the difference in water surface elevations exceed a prescribed value. The worst case occurs when a very wide, shallow cross section with a large cross section flow area has to discharge into a narrow deep cross section. When surging occurred, the cross sections were adjusted to reduce the difference in flow areas.

Finally, the when the channel cross section depths created adverse slope conditions in the channel profile, the channel depth and bed elevations were adjusted to achieve a smooth slope. Since the channel length ranged from 1200 ft to 2800 ft within the grid element, scour hole and pool could not be appropriately modeled and local adverse slope conditions were eliminated.

Several FLO-2D simulations were required to adequately calibrate the predicted discharges for the 1996 Green River hydrograph. Once this task was complete, a new tributary inflow hydrograph data file was developed for the 1997 high flow season. FLO-2D was then applied again using the 1997 discharge data and the same FLO-2D data base.

FLO-2D Green River Predicted Hydrograph Results

FLO-2D predicts a hydrograph for every channel grid element (every 2000 ft) throughout the Green River system from Flaming Gorge to the Colorado River confluence. A daily discharge output time interval was implemented for the Green River simulation. One hundred days of the 1996 and 1997 high flow seasons were modeled starting with April 1. The accuracy of the results can viewed with the HYDROG post-processor program. A series of predicted hydrographs are compared with the known discharge locations in Appendix C for 1996 and Appendix D for 1997. The accuracy of the numerical routing is monitored by the volume conservation in the model which is listed in either the BASE.OUT or SUMMARY.OUT files.

There is an excellent correlation between the FLO-2D predicted and the measured discharge hydrograph at the USGS Jensen gage. The cross section at this location is relatively stable with a cobble bed across most of the channel. The computed results compare well with the measured data for both 1996 and 1997. The Green River USGS gage hydrographs are also presented in the Appendices. The results show greater disparity between the predicted and measured discharge hydrographs, however, the timing of the various peaks and troughs in the hydrograph is excellent. The difference between the predicted and measured hydrographs can be attributed to the following considerations:

- Small unmeasured tributary inflow between Jensen and Green River.
- Possible storm inflow reflected in a couple of spikes in the measured discharge.
- Canal diversion at Green River.
- Estimated USGS discharges at the Green River gage (discharge data errors).
- Variable infiltration and evaporation losses in the reach from Jensen to Green River.

Despite these potential sources of error in the correlation, the Green River USGS measured gage data compare very favorably with the FLO-2D predictions. It should be noted that the Green River gage appears to be subject to variation in the stage for a given discharge related to potential sediment deposition and backwater effects from the vegetated braided islands downstream. In addition, this gage also experienced problems in recorded data for both 1996 and 1997. A total of 7 and 17 daily discharges were estimated for the Green River gage in April, May and June for 1996 and 1997.

The level loggers located at the various sites also experienced a number of difficulties. Overall, the level loggers provide a valuable correlation for discharge magnitude and timing to compliment the data from the two USGS gages which are separated by 197.5 river miles. In 1996 and 1997, the Echo Park and Ouray National Wildlife Refuge level loggers experienced sedimentation in the well pipe. Only a limited number of days of accurate stage readings were recorded. The Bonita Bend level logger in Canyonlands in 1996 had bracket supports detach from the bedrock near the peak discharge and the level logger pipe slipped down into the river creating a stage shift. During the rest of the season, the level logger shifted with the river stage invaliding much of its data. Some of the data was salvaged by adjusting the records for the stage shift but small continuous shifts in the level logger position were cumulative and a large portion of the discharges computed for the recessional limb of the hydrograph are inaccurate as shown in the appendix figures. The level logger located just downstream of the White River has a small channel that bypasses the level logger at very high flows. In 1996, the unmeasured flow in this small channel was negligible. In 1997, the unmeasured flow was significant as shown in Figures D.2 and D.4 in Appendix D. All the level logger data was subjected to the following considerations:

- The stage-discharge rating curve for each level logger had only a limited number of discharge measurements (5 to 10). There were very few discharge measurements at peak flows to improve the accuracy of the rating curves.

- Most of the level loggers were located in relatively stable cross sections, but at high flow, the variation in stage discharge relationship related to scour or sediment deposition may effect the discharge estimates. There may also be a change in the hydraulic roughness at high flows which effect the stage-discharge rating curve.

Despite these limitations, the USGS gages and level loggers in the Green River provide a good monitoring system with which to correlate the FLO-2D model hydrograph predictions. After calibrating the 1996 discharge hydrographs by varying the infiltration parameters and channel roughness to generate a good match between the predicted and measured hydrographs, FLO-2D routee the 1997 Green River flows. The FLO-2D 1997 predicted hydrograph at Jensen is excellent and predicted hydrographs throughout the rest of the Green River system are very good. The FLO-2D model can now be applied to any historic year of flows or to any future river forecasts in the Green River.

To demonstrate the utility of the FLO-2D model, two additional high flow scenarios for 1997 were simulated. The first scenario included routing the 1997 unregulated Green River flows at Greendale, Wyoming (i.e. without the storage effects of Flaming Gorge and Fontenelle Reservoirs). The results are shown in the Appendix E Figures. The 1997 unregulated Greendale hydrograph was provided by the Bureau of Reclamation. The rest of the actual 1997 Green River tributaries inflows were input for this routing scenario. The Green River 1997 unregulated hydrograph at Greendale has an approximate peak of 21,060 cfs on June 13. Comparably, tThe Yampa River had a peak of about 21,400 cfs on June 4. The FLO-2D computed unregulated peak was 36,220 cfs at Jensen and 38,600 cfs at Green River compared to the actual peak discharges of 24,780 cfs and 31,900 cfs respectively. In Canyonlands, the FLO-2D computed unregulated peak was 40,350 cfs which is slightly greatly than the estimated bankfull discharge (FLO, 1995).

The second flow scenario also involved the 1997 unregulated flows at Greendale, but the discharge was limited to the maximum jet tube discharge of 8,570 cfs. All the 1997 Greendale unregulated discharges were reviewed and if the flow exceeded 8,570 cfs, the input FLO-2D model was 8,570 cfs. The other 1997 Green River tributaries inflows were not modified. The results are presented in the Figures in Appendix F. The FLO-2D computed peaks were 29,260 cfs at Jensen and 34,000 cfs at Green River. This represents a peak discharge increase over the actual flows of 4,480 cfs at Jensen and 2,100 cfs at Green River. The inflow volume to the Green River FLO-2D system associated with the higher jet tube releases is 221,400 acre-ft which corresponds to 166,900 acre-ft of flow into the Colorado River during the 100 day simulation period.

Conclusions

The FLO-2D model can predict discharge at any 2000 ft location in the Green River system by routing Flaming Gorge releases and tributary inflows using a full dynamic wave approximation to the momentum equation. Overbank floodplain storage and infiltration are simulated to improve the prediction of floodwave attenuation. FLO-2D conserves volume which makes it attractive as a management tool. The model can be used to evaluate the effects of Flaming Gorge operation on floodplain inundation at Ouray or on the timing, duration and magnitude of discharge in lower Green River in Canyonlands.

The Green River FLO-2D model was calibrated with 100 days of the 1996 high flow hydrographs. The model was then applied to 100 days of the 1997 Green River high flow hydrograph. The FLO-2D predicted hydrograph was compared with the actual 1997 flows at the USGS Jensen and Green River gages. The excellent correlation between the predicted discharge and the actual flows justifies future application of the model to predict historic or future flow scenarios.

The utility of the FLO-2D model is demonstrated by simulating the 1997 unregulated Green River flows at Greendale, Wyoming. Simulating the flows without the effects of Flaming Gorge and Fontenelle Reservoir indicated that bankfull discharge would have been exceeded in Canyonlands in 1997. Based on the FLO Engineering (1995) report, the floodplain in Canyonlands is hydrologically disconnected from the river's post-1963 flow regime; bankfull discharge has an approximate frequency of once in fifteen years. In this example, FLO-2D is a tool to evaluate historic flow scenarios.

In a second unregulated 1997 Greendale flow scenario, the Flaming Gorge jet tube releases were limited to a maximum of 8,570 cfs. The increased in peak discharge was compared to the actual 1997 flows at Jensen and Green River. If the Flaming Gorge jet tube discharge of 8,570 cfs had occurred at the appropriate time and for an appropriate duration, the predicted peak discharge of 29,200 cfs at Jensen would have created widespread floodplain inundation in the Ouray reach. This flow scenario illustrates the flexibility of the FLO-2D model as a management tool.

The development of the FLO-2D model represents the compilation of the results of several research projects and culmination of the level logger discharge monitoring program over the last two years. Those projects included the flooded bottomlands project at Ouray and in Canyonlands, various channel monitoring projects which provided channel geometry data, and the multifarious razorback sucker spawning bar projects. All these projects contributed to development of the FLO-2D data base including floodplain topography, discharge estimates throughout the Green River system, bankfull discharge estimates, calibration of hydraulic roughness values, and channel cross section geometry. These projects also provided valuable insight and understanding of the entire Green River system which was essential to assigning the hydraulic parameters and calibrating the model.

Recommendations

There are several recommendations that could improve the FLO-2D Green River flow simulation including:

- Extending the FLO-2D grid system up the tributaries to USGS gaging stations (Maybell, Yampa River; Lily, Little Snake River; White and Duchesne Rivers).

- Refining the floodplain elevations to improve the prediction of the areas of flood inundation. The 1996 and 1997 IFR aerial photography could be used to calibrate the floodplain elevations for inundated grid element on these years.

- Modeling sediment transport. FLO-2D has a sediment transport component and sediment movement in the Green River system can be simulated. The Bureau of Reclamation has a project to apply FLO-2D to the Rio Grande in New Mexico and has requested the application of the sediment transport component.

Now that the FLO-2D data base for the Green River has been constructed, any combination of flow scenarios can be simulated. Either historical flow scenarios or future flow forecasts can be simulated. Both Flaming Gorge and tributary inflows can be varied. One approach for forecasting peak flows would be to select a representative water year which reflects the potential basin snowpack for the next runoff season. This forecast analysis could be accomplished on a tributary basin level by developing tributary inflow forecasts to Green River. Using the historical hydrographs for a selected year(s), various Flaming Gorge releases could then be superimposed on the tributary inflows to determine preferred flow regimes for timing, peak and duration at selected locations in the Green River system. This adaptive management strategy could be applied to enhance river fish habitat conditions, provide channel morphology maintenance flow or increase the magnitude and duration of the overbank flooding. It could also be used to predict or enhance the timing of the opening backwater fish habitats in the lower Green River.

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